

A Procedure for Rapid Visual Screening for Seismic Safety of Wood-Frame Dwellings with Plan Irregularity

Kraisorn Lucksiri^a; Thomas H. Miller^b, Rakesh Gupta^c,
Shiling Pei^d, John W. van de Lindt^e

^a Graduate Student. School of Civil and Construction Engineering and Dept. of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331, USA. Email: kraisorn.lucksiri@oregonstate.edu

^b**Corresponding Author.** Associate Professor. School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331, USA. Email: thomas.miller@oregonstate.edu
(541) 737-3322; (541) 737-3052 (fax)

^c Professor. Dept. of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331, USA. Email: rakesh.gupta@oregonstate.edu

^d Assistant Professor. Dept. of Civil and Environmental Engineering, South Dakota State University, Brookings SD 57006, USA. Email: Shiling.Pei@sdstate.edu

^e Professor and Drummond Chair. Dept. of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL, 35487, USA. Email: jwvandelindt@eng.ua.edu

ABSTRACT

This paper highlights the development of a rapid visual screening (RVS) tool to quickly identify, inventory, and rank residential buildings that are potentially seismically hazardous, focusing on single-family, wood-frame dwellings with plan irregularity. The SAPWood software was used to perform a series of nonlinear time-history analyses for 480 representative models, covering different combinations of plan shapes, numbers of floors, base-rectangular areas, shape aspect ratio, area percentage cutoffs, window and door openings, and garage doors. The evolutionary parameter hysteresis model was used to represent the load-displacement relationship of structural panel-sheathed shear walls and a ten parameter CUREE hysteresis model for gypsum wallboard sheathed walls. Ten pairs of ground motion time histories were used and scaled to four levels of spectral acceleration at 0.167g, 0.5g, 1.0g, and 1.5g. An average seismic performance grade for each model was generated based on the predicted maximum shear wall drifts. Five seismic performance grades: 4, 3, 2, 1, and 0, are associated with the 1% immediate occupancy drift limit, 2% life safety limit, 3% collapse prevention limit, 10% drift, and exceeding 10% drift, respectively. The obtained average seismic performance grades were used to develop a new RVS tool that is applicable for checking the seismic performance of either existing or newly designed single-family, wood-frame dwellings. It examines the adequacy of the structure's exterior shear walls to resist lateral forces resulting from ground motions, including torsional forces induced from plan irregularity.

Key Words: seismic analysis, wood structures, configuration

1. Introduction

Damage caused to residential wood-frame dwellings from the 1994 Northridge, California earthquake has raised concerns. It is estimated that approximately 48,000 housing units were rendered uninhabitable [1], and estimated property loss in residential wood-frame buildings was at least \$20 billion. Private insurance companies paid a total of about \$12.3 billion in claims, with approximately \$9.5 billion (78% of total) for residential claims [2]. Damage was found to range from minor non-structural damage to a severe, non-habitable level.

In general, the simplest damage and loss estimation procedures for existing buildings involve rapid visual screening (RVS) where the evaluation is primarily based on visual inspection with no engineering calculations involved. For single-family, wood-frame dwellings, the currently available RVS tools are the second edition of FEMA 154 [3], its supporting document, FEMA 155 [4], and ATC 50-1 [5]. These tools were, however, found to have some limitations which provide the impetus for this study. First, FEMA 154 was originally developed for macroscopic loss estimation for a large inventory of buildings, so its application to building-specific cases is not recommended. Second, although ATC 50-1 was developed specifically for detached, single-family, wood-frame dwellings, and it looks at a house as an integrated unit with considerations of various vulnerability sources that affect seismic performance, it was, however, particularly developed for the city of Los Angeles. Finally, indications of potential seismic vulnerability sources in both RVS tools are based on a simple “yes” or “no” categorization, which is only really suitable for identifying the presence of building features such as unreinforced masonry chimneys and cripple walls. This approach may not be appropriate for plan irregularity where the effect varies from case to case and depends on the type (re-entrant

corner, door/window opening, etc.) and degree of irregularity (size of door/window opening, offset ratio of re-entrant corner, etc.). Almost all houses in the US have some type of plan irregularity and many have vertical irregularities as well.

This paper describes the development of an RVS tool for examining plan irregularity in single-family, wood-frame dwellings. This is the second phase of the study. In phase 1, basic data were developed and a numerical investigation performed on the effect of plan configuration on seismic performance of single-family, wood-frame dwellings [6]. 151 models were developed using observations of 412 dwellings of rectangular, L, T, U, and Z shapes in Oregon. A nonlinear, time-history program, Seismic Analysis Package for Woodframe Structures, was the analysis platform. Models were analyzed for 10 pairs of biaxial ground motions (spectral accelerations from 0.1g to 2.0g) for Seattle. Configuration comparisons were made using median shear wall maximum drifts and occurrences of maximum drifts exceeding the 3% collapse prevention limit. Phase 1 showed that plan configuration significantly affects performance through building mass, lateral stiffnesses and eccentricities. Irregular configuration tends to induce eccentricity and cause one wall to exceed the allowable drift limit, and fail, earlier than others. Square-like buildings usually perform better than long, thin rectangles. Classification of single-family dwellings based on shape parameters, including size and overall aspect ratio, plan shape, and percent cutoff area, can organize a building population into groups having similar performance, and be a basis for including plan configuration in rapid visual screening.

The objective of this paper (Phase 2) is to develop a rapid visual screening tool for single-family wood-frame dwellings with plan irregularity that can be used by the same audience as FEMA 154 [3], including building officials and inspectors, government agencies, insurance companies and private-sector building owners, to identify, inventory, and rank buildings that are

potentially seismically hazardous. The new RVS tool also uses the same concept of “sidewalk survey” approach and a “data collection form” in which the screener can complete the evaluation based on visual observations from the exterior. In this project, only the effect of plan irregularity on torsional forces was examined, and the effect of stress concentrations at reentrant corners was not included. Non-linear, time-history analysis was used to study variations in plan configuration including plan shapes, sizes, window and door openings, and garage doors. Future work will include an implementation of this new RVS tool for more realistic building configurations and openings in walls. The results will be compared to predictions from FEMA 154 [3] and tier 1 of ASCE/SEI 31 [7].

2. Methodology

The development methodology is organized into two parts: (i) building configuration parameters and (ii) building seismic response prediction.

2.1 Building Configuration Parameters

Selection of the building configuration parameters, discussed in the following sections, for the models was considered based on two aspects. First, the range of parameters covers the typical variations in plan shapes and plan irregularity found in a particular type of building. Second, each model represents the worst-case scenario for dwellings of similar configurations. Details of selected configuration parameters were summarized into 2 groups: (i) shape parameters and (ii) openings-related parameters.

2.1.1 Shape Parameters

Shape parameters are used to specify plan shape configurations of buildings. A set of parameters including plan shape, base-rectangular area, overall shape ratio, and percent cutoff, introduced in Luckisiri et al. [6] was used.

As illustrated in Figure 1, each building plan originates from a base-rectangular area of size $a \times b$. Overall *shape ratio*, R , ($R = b/a$), is used to represent the overall proportions of a plan shape, i.e. a square plan shape ($R = 1.0$) or a rectangular plan shape ($R \neq 1.0$). For rectangular, L, and Z shapes, the dimension “ a ” is always assigned to be longer than “ b ”. For T and U shapes, “ a ” always refers to the side shown in the figure and can either be longer or shorter than “ b ”. This base-rectangular area is then cut-off to achieve a particular plan shape. The cutoff areas are shown in Figure 1 as grey-shaded portions. *Percent cutoff* (C_p) area indicates the amount of cutoff area relative to the area of the base rectangle, and is also a way to specify the relative size of reentrant corners. The value of C_p is always less than 1.0. For example, percent cutoff area equals $100 \cdot [(c \cdot d) / (a \cdot b)]$ for the L-shape in Figure 1.

To specify the configuration for a plan shape, two additional parameters are required: *cutoff shape ratio*, R_c , and *cutoff ratio*, C_r (for T and Z shapes). Cutoff shape ratio represents the direction of cutoff area relative to the base dimension “ a ”. For example, it is the ratio of dimension “ c ” (parallel to “ a ”) to “ d ” (parallel to “ b ”) for the L-shape shown in Figure 1. R_c can either be smaller or greater than 1.0. Cutoff ratio is used for T and Z shapes to indicate the relative size between two cutoff areas. For the T-shape, cutoff ratio equals the ratio of (the smaller) *cutoff area 1* to (the larger) *cutoff area 2*. The maximum value of cutoff ratio is 1 (equal cutoff areas). Thus, the selected shape parameters are summarized as follows:

2.1.1.1 Plan Shape

Five plan shapes commonly used in the design of single-family, wood-frame dwellings were selected, including rectangles, L, T, U, and Z shapes.

2.1.1.2 Base-Rectangular Area

The overall upper limit of the base-rectangular area is 465 m^2 (5000 ft^2). This selection was based on the FEMA 154 [3] definition for the W1 structural type, light wood-frame, residential and commercial buildings with floor area less than 465 m^2 (5000 ft^2). Observed data from phase 1 on areas for various plan shapes are shown in Table 1. Although the data collected using Google Earth may include some 2-story buildings, they were used directly for base-rectangular area selection for 1 story models. Selections for 2-story buildings were based on the FEMA 154 definition for W1 alone. A summary of the selected base-rectangular areas is shown in Table 2.

2.1.1.3 Shape Ratio and Percent Cutoff

For both shape ratio and percent cutoff, upper and lower bounds determined from phase 1, the observed mean ± 2 * standard deviations (SD) with considerations of the corresponding maximum and minimum values, were used. The upper bound of shape ratio ($R= 1.0$) represents square plan shapes, while the lower bound ($R \neq 1.0$) represents rectangular shapes. The upper and lower bounds of percent cutoff represent building plans with large and small reentrant corners, respectively. Table 3 summarizes the selected values for both parameters.

For each combination of shape parameters in Table 3, the final shape for each model, specified by cutoff shape ratio and cutoff ratio, was based on the worst-case-scenario model determined from Lucksiri et al. [6]. Selection of a worst-case-scenario model, for each

combination of R and C_p , was performed by comparison of median maximum drifts of models with variations of R_c and C_r (for T and Z shapes) over a range of spectral accelerations, S_a . The lower bound was assumed to be the S_a value that induces approximately 12.7 mm (0.5 in.) median maximum drift, and the upper bound is that producing 73.1 mm (2.88 in.) median maximum drift (3%). The model that has the largest median maximum drift (over the range of spectral accelerations) is considered the worst-case-scenario.

2.1.2 Openings-Related Parameters

Two sources of openings included in the development were windows and doors, and garage doors. The amount of windows and doors is specified in terms of percent openings which is the relative length (horizontal dimension) of windows and doors compared to the length of the wall where they are located. Openings were made in walls in both major directions of the buildings. For rectangular shapes ($R \neq 1.0$), it is common to have more windows and door openings along the long side than the short, so four different combinations of percent openings (Long % | Short %) were included: 60|30, 60|0, 30|15, and 30|0. For square shapes ($R = 1.0$), percentage openings were assumed to be equal on walls in both major directions, and the 60|60 and 30|30 combinations were included.

Models were also analyzed for cases with and without a garage door opening. When a garage door is present, its location was assumed to be on the most critical wall (a wall where maximum drift tends to occur, as described in Lucksiri et al. [6] to enhance the effect of torsion. This, however, limits the size of a garage door to the length of the most critical wall. As a result, a 3.05 m (10-ft) wide single car garage door is assumed for dwellings with total net floor area

less than or equal to 279 m^2 ($3,000 \text{ ft}^2$), and a 5.49 m (18-ft) wide double car garage door is assumed for dwellings with total net floor area greater than 279 m^2 ($3,000 \text{ ft}^2$).

Based on these parameter variations and combinations, a set of representative models was created. Table 4 shows an example of a case study matrix for 1-story, 139 m^2 ($1,500 \text{ ft}^2$) base-rectangular area, L-shape models where 24 representative models were produced. Case study matrices for other models with different shapes and numbers of stories were set up similarly and are given in Lucksiri [8]. As a result, a total of 480 representative models was obtained as summarized in Table 5.

2.2 Seismic Response Prediction

2.2.1 Structural Modeling

In general, a structural model consists of a vertical shear wall, and horizontal elements which include the roof, ceiling, and floor. Shear walls are located on the perimeter of the plan shape with structural sheathing panels on one side and gypsum wallboard on the other. Story height is assumed to be 2.44 m (8 ft). Wall dead loads are transferred to the roof diaphragm based on tributary height. Magnitudes of shear wall and partition wall dead loads were based on ASCE 7-05 [9] with a dead load of 527 N/m^2 (11 psf) for exterior shear walls and a uniformly distributed load per floor area of 718 N/m^2 (15 psf) for partition walls. For horizontal elements, seismic mass includes the roof, ceiling, and floor, as 478 N/m^2 (10 psf), 191 N/m^2 (4 psf), and 383 N/m^2 (8 psf), respectively.

Structural elements of the buildings are assembled into a “pancake” model configuration [10] where horizontal diaphragms are connected by zero-height shear wall spring elements. The

pancake model assumes all diaphragms to be rigid with infinite in-plane stiffness, and captures the effect of torsional moment due to eccentricities.

2.2.2 Structural Panel Sheathed Shear Walls

An evolutionary parameter hysteretic model (EPHM) [11, 12] was selected to represent the nonlinear force-deformation relationship of structural panel sheathed shear walls as it is capable of providing a better simulation of the post-peak envelope behavior than a linearly decaying backbone model. Values of EPHM parameters are from a SAPWood database generated at the connector level using the SAPWood-NP program. Linear interpolation was used to obtain parameters for different wall lengths. Since shear wall configurations can be different, it is considered conservative and appropriate to use minimum values in the database for other ductility- related parameters. The assumed nail spacing values for edge and field are 150 mm (6 in.) and 300 mm (12 in.), respectively, with a stud spacing of 406 mm (16 in.). EPHM parameters for this specific wall configuration are described in the SAPWood software and user's manual [13].

2.2.3 Gypsum Wallboard Sheathed Walls

The contribution of gypsum wallboard (GWB) sheathed walls was included in the analysis. Since the degradation of GWB is sudden, the CUREE 10-parameter model was considered suitable for representing the load-deformation relationship. Parameters used (Table 6) were based on the available set of parameters for a 2.4 m x 2.4 m (8 ft x 8 ft) GWB wall [14]. It was assumed that the initial stiffness (K_0) and ultimate capacity (F_0) are proportional to the wall length for walls with lengths other than 2.4 m (8 ft). This CUREE hysteretic model was superimposed with the

EPHM model to build up exterior shear walls with a structural panel on the exterior surface and GWB on the interior surface.

2.2.4 Ground Motion Suite

Ten pairs of ground motion time histories developed for Seattle [15], having probabilities of exceedance of 2% in 50 years (typically associated with collapse prevention performance), were used. These ground motions were developed considering 3 types of seismic sources including (i) shallow Seattle crustal faults (at depths less than 10 km), (ii) the subducting Juan de Fuca plate (at depths of about 60 km), and (iii) the plate interface at the Cascadia subduction zone (about 100 km west of Seattle).

2.2.5 Damping Ratio

For this study, the majority of the damping is accounted for by nonlinear hysteresis damping in the EPHM springs. A viscous damping ratio of 0.01 was used based on SAPWood model verification [16,17], where analyses with a very small viscous damping ratio (usually 0.01) yielded good agreement with shake table test results.

2.2.6 Nonlinear Time-History Analysis

SAPWood v1.0 was the analysis platform. The natural period of each building was determined based on the seismic mass, height of the building, floor plan configuration, and amount of shear wall openings. Examples of the variation in natural period were illustrated in Lucksi et al. [6]. A period of 0.2 sec was used only for ground motion scaling, i.e. each input record was scaled based on the spectral acceleration (S_a) of a single degree of freedom system with a damping ratio

of 0.05 and a natural period of 0.2 sec. Ground motion scaling was performed so that when the first component of ground motion reached the specified S_a , the same scaling factor was then applied to the second component. The scaling used is unbiased and implemented with the intention to fix the intensity in one excitation direction while keeping the intensity ratio between the two components the same as the original record, partially because building damage is often driven by excitation in one direction. However, although a common procedure in many situations including shake table testing, this scaling is not as robust as some other possible methods (such as using the geometric means of the two horizontal components).

Each orthogonal pair of ground motions was applied twice (rotated 90 degrees) to each model. The S_a targets were the upper limits of S_a specified for each seismic region in FEMA 154 [3] (Table 7). However, the high seismicity region was separated into High 1 and High 2 regions with their corresponding S_a limits of 1.0g and 1.5g, respectively, to increase the resolution of the high seismic region categories. Accordingly, for each level of spectral acceleration, ten maximum shear wall drifts resulting from the ten input ground motions were obtained through nonlinear time history analysis.

2.2.7 Seismic Performance Grade

The proposed RVS method uses numerical seismic performance grades, ranging from 0 to 4, to classify different performance levels. Similar to the FEMA 154 [3], the higher score represents better seismic performance for the buildings. The conversion criteria used to transform the analysis results, i.e. maximum shear wall drifts, to performance grades are summarized in Table 8. Conceptually, grades 4, 3, and 2 are associated with the 1% immediate occupancy (IO) drift limit, 2% life safety (LS) limit, and 3% collapse prevention (CP) limit, respectively.

For each model, at a particular level of S_a , the conversion was made for each of the ten maximum drifts (resulting from ten input ground motions). The average performance grade (G_{avg}) was determined by averaging all ten performance grades accordingly to represent the overall performance of the modeled structure.

3. Results and Discussion

3.1 Overall Seismic Performance

The overall seismic performance of the studied models is presented and discussed. It is emphasized that no interior shear walls or interior partition walls are considered in the analyses as it is assumed that the structural details are obtained from a “side-walk survey” only. There is a bias in the approach to overestimate the response of larger residential buildings with many interior walls that are neglected in the analysis.

Table 9 shows the overall ranges of average performance grades for all the models when classified by number of floors and base-rectangular area. Distributions of these grades are also shown in Figure 2. In general, across all selected ground motions, group 1-S has the best performance and is the group of single-story buildings with small base-rectangular areas, while group 2-L, 2-story models with large base-rectangular area, is the group that performs worst. Single-story houses generally perform better than 2- story houses even of a small size.

As shown in Table 9, for the low seismicity region, all single story models satisfy the objective of immediate occupancy, i.e. all G_{avg} scores equal 4.0. For 2-story models, G_{avg} ranges from 3.4 to 4.0 for low seismicity, indicating that lateral and torsional forces from ground motion do not cause severe damage. The worst performance ($G_{avg}= 3.4$) is in the range of the life safety to immediate occupancy performance limits. For the moderate seismicity area, all models were

able to meet the objective of collapse prevention with the overall range of seismic performance grades from 2.9 to 4.0 and 1.8 to 3.8 for single-story and 2-story dwellings, respectively.

High 1 and high 2 seismic regions are where the effects of plan configuration and plan irregularity become more obvious and earthquake-induced damage can be severe. For high 1, wide ranges of grades were observed from 0.9 to 3.2 and 0.4 to 2.6 for 1-story and 2-story models, respectively. For high 2, the single-story group continues to have a wide range with the minimum grade as low as 0.2 and a maximum grade of 3.2. However, at this level, none of the 2-story models was able to meet the collapse prevention objective, and grades range from 0.1 to 1.1.

Figure 3 shows the relationship between base-rectangular area and average performance grades for 1-story, square, models. In general, average performance grade decreases as the base-rectangular area increases. For 1-story models, this effect was not evident in the low seismicity region where all models perform well, but it becomes clearer for moderate seismicity. For high 1, the grades, especially the lower bounds, decrease as the base-rectangular area increases. This is because the effects of increased mass (from an increased base-rectangular area) and the nonlinear properties of shear walls become more obvious at this level of spectral acceleration. For high 2, while the lower bounds approach zero, the trend is still observable for the upper bounds. This same trend was also found for 2-story, rectangular models (Figure 4). Since the first story shear walls are supporting seismic mass from the second floor in addition, the effect was observable even for low seismicity.

The amount (percentage) of openings and a garage door directly affect the overall lateral stiffness of buildings. As a result, for buildings with the same base-rectangular area and percent cutoff, the more openings present, the worse is the seismic performance. Examples are shown in

Figures 5 and 6. Figure 5 is for a 1-story, L-shape, 139 m^2 ($1,500 \text{ ft}^2$) base-rectangular area, $R=0.5$, and $C_p=10\%$, while Figure 6 is for a 2-story, L-shape, $2,232 \text{ m}^2$ ($24,250 \text{ ft}^2$) base-rectangular area, $R=0.5$, $C_p=10\%$. Buildings tend to perform worse as the opening on the short side becomes larger, i.e. comparisons made between 30|00 vs 30|15 or 60|00 vs 60|30 percent openings cases. For buildings with the same configuration and window/door percent openings, the presence of a garage door generally decreases their seismic performances, as expected (i.e. comparisons made between a triangular dot (with garage door) and a circular dot (no garage door) at each level of percent openings. The plots also show the effects of shear wall nonlinearity in that when a garage door is present on a wall having window/door openings, it tends to have a stronger negative effect on seismic performance than having a garage door installed on a solid wall (for example, the comparison with and without a garage door, between the 60|00 and 60|30 cases). However, this trend did not exist for high 2 seismicity for 1-story, and high 1 and high 2 for 2-story, since the ground motions are so severe that they cause G_{avg} to approach zero regardless of the amount of percent openings.

Figure 7 shows histograms of the maximum difference of G_{avg} between L, T, and Z shapes of the same configuration and plan irregularity. The comparison was made for all 48 cases of single story models and 48 cases for 2-story models. For all seismicity regions, the range of difference that has the highest frequency is 0.0 to 0.1. For more than 80% of all cases, the differences are less than 0.3. This implies a strong similarity in seismic performance for these building shapes because these three shapes, when having the same base-rectangular area and percent cutoff, have the same seismic mass as well as the total lateral stiffness along both major directions. The observed differences of G_{avg} result from different eccentricity characteristics due to variation in numbers and locations of cutoff areas. So, it is considered reasonable to use the

minimum grades (among the comparable L, T, and Z shapes) to develop scoring tables which are applicable for these plan shapes.

3.2 Development of Grading Sheets

The intent of the grading sheet development is to provide a simple evaluation form that would allow an inspector to assign a building its seismic performance grade (reflecting its plan shape and irregularities) that represents the expected seismic performance at a specified level of spectral acceleration. Grading sheets were developed separately for each group of single-family, wood-frame dwellings classified by plan shape and number of floors. For each group, the grading sheet is a single page except for that of single- story T and U shapes where an extra page for the 4,500 ft² base-rectangular area was added. Figure 8 shows the grading sheet for 1-story L, T, and Z shapes.

The grading sheet is organized into 5 areas as shown in Figure 8. The top left area (area #1) shows plan shapes and defines parameters. Next to the shapes is a scale showing the relationship between the final score and the expected performance level. The middle left area (area #2) is provided for shape parameter calculation. An area to sketch a plan view of the structure is located at the bottom left of the page (area #3). The top right area (area #4) is for basic information about the building and RVS, such as the address, date, and name of screeners. A space to record the expected spectral response (S_a) for the site under considerations is also provided. The remaining space (area #5) on the right side is where the scoring table is located.

All (1,920) average performance grades (G_{avg}) obtained from the analysis of 480 models at 4 levels of S_a were arranged into their corresponding locations in the scoring table (the grading sheet is organized by plan shape and number of floors). The table was designed to have a similar

appearance and scoring concept as FEMA 154 [3], where the scoring consists of 3 major components: basic score (BS), score modifiers (SMs), and final score (FS), where $FS = BS - SMs$. For this new RVS tool, the basic score refers to the average performance grade of a basic model. For square plan shapes ($R = 1.0$), basic models are those with the least openings, i.e., 30|30 percent openings with no garage door. Similarly, for rectangular plan shapes ($R \neq 1.0$), basic models are the models with 30|0 percent openings with no garage door. The basic scores and score modifiers were determined for each group of models having the same plan shape, number of floors, overall shape ratio, base-rectangular area, and percent cutoff. The difference in G_{avg} between models having different percent openings (without garage door) compared to the basic model is reflected in percent opening score modifiers. The maximum differences in G_{avg} between the “with-garage” and “without-garage” cases, determined from all pairs, were used as the garage door score modifier for the group. An example of the developed grading sheet for 1-story for L, T, and Z shapes is shown in Figure 8. Figure 9 shows part of a grading sheet (areas 1 and 5) for 2-story L, T, and Z shapes.

An example application of the grading sheet is illustrated in Figure 8, where a single story L-shape building is examined. The observed plan configuration data were recorded and shown in area 2. The building has a base-rectangular area of 279 m^2 ($3,000 \text{ ft}^2$), percent cutoff of 9.7%, and a garage door. Percent openings along the long and short sides were estimated to be 60% and 30%, respectively. The overall plan configuration was sketched in area 3. Assuming that Life Safety was the performance objective, the 2008 U.S. Geological Survey (USGS) National Seismic Hazard Maps with 10% probability of being exceeded in 50 years were used. The expected spectral acceleration, calculated including the site coefficient, was determined based on the procedure in ASCE/SEI 31 [7], and was assumed equal to 1.0 for this example. As a result,

from the high 1 scoring table, the basic score for this building is 3.0. The score modifiers for window and door openings and garage door are -1.1 and -0.6, respectively. This leads to a final score of 1.3 which is less than 2.0, so the building fails to meet the collapse prevention drift limit and a more detailed investigation is recommended.

4. Conclusions

1. The new rapid visual screening (RVS) tool, developed in this study, examines the adequacy of single-family, wood-frame dwellings in Oregon to resist lateral forces resulting from ground motions and torsion induced from plan irregularity. The evaluation procedure takes into consideration the shape of the floor plan, number of stories, base-rectangular area, percent cutoff, and openings from doors/windows and garage doors.
2. Application of the proposed RVS tool does not cover other sources of seismic vulnerabilities such as the effects of forces at reentrant corners, vertical irregularity, liquefaction, slope failure, unreinforced masonry chimneys, and foundation connections. Other issues such as different nail spacing for wall lines with large openings should also be further investigated.
3. The tool can be used together with FEMA 154 to identify whether a building with a particular plan shape and plan irregularity, focusing on torsional effects, can be potentially hazardous. Since performance grades from the new RVS method relate the predicted maximum shear wall drifts to immediate occupancy, life safety, and collapse prevention limits, the screener can use a final score of 2.0, which relates to collapse prevention performance, as a cutoff grade. It is also possible to incorporate this tool into

Tier 1 (screening phase) of ASCE/SEI 31 to check the adequacy of the exterior shear walls in an existing building.

4. Using non-linear time-history analysis with pancake model, the effect of torsion due to mass eccentricities is included. Duration of ground motion shaking and number of cycles are taken into account through the numerical integration of the equation of motion. Since the development was based on a worst-case-scenario concept, and the representative models were based only on structural details observable from a side-walk survey (no contributions from any interior walls were included), the predicted results are considered to be reasonable and conservative for evaluations to meet the target performance objectives.
5. When ignoring the contributions from interior walls, increasing the base-rectangular area degrades the overall seismic performance. Buildings with two stories, a larger percentage of openings, and having a garage door were found to be more vulnerable to seismic events, as expected. In general, plan shape and plan irregularity were found to be important features especially in houses located in high 1 and high 2 seismicity regions, as they could potentially lead to severe damage. For low and moderate seismicity, the performance ranges from satisfying the collapse prevention limit to the immediate occupancy limit.

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Table Captions

Table 1. Observed areas of plan shapes from phase 1 [6]

Table 2. Base-rectangular areas selected for RVS development

Table 3. Selected shape ratios and percent cutoffs

Table 4. Example of case study matrix for 1-story, 139 m² base-rectangular area, L-shape models

Table 5. Summary of total number of representative models

Table 6. CUREE parameters for 2.4 m (8 ft) by 2.4 m (8 ft) GWB wall model

Table 7. Seismic region definition

Table 8. Performance grade conversion criteria

Table 9. Minimum and maximum values of average performance grades (G_{avg}) classified by number of floors and base-rectangular area

Table 1 Observed areas of plan shapes from phase 1 [6]

Plan Shape	Observed Net Floor Area, m ² (ft ²)		
	Minimum	Average	Maximum
Rectangle	52 (560)	162 (1,747)	297 (3,200)
L	72 (780)	185 (1,987)	293 (3,150)
T	88 (948)	215 (2,310)	387 (4,170)
U	173 (1,860)	247 (2,661)	436 (4,688)
Z	100 (1,074)	203 (2,185)	308 (3,316)

Table 2. Base-rectangular areas selected for RVS development

No. of Stories	Base-rectangular Area	Plan Shape				
		Rectangle	L	T	U	Z
1	139 m ² (1,500 ft ²)	X	X	X	X	X
	279 m ² (3,000 ft ²)	X	X	X	X	X
	418 m ² (4,500 ft ²)			X	X	
2	2x116 m ² (2x1,250 ft ²)	X	X	X	X	X
	2x232 m ² (2x2,500 ft ²)	X	X	X	X	X

Table 3. Selected shape ratios and percent cutoffs

R	Cp (%)	Rect.	L	T	U	Z
0.5	0	x				
	10		x	x		x
	30		x	x		x
1.0	0	x				
	5				x	
	10		x	x		x
	15				x	
	30		x	x		x
1.3	5				x	
	15				x	

Table 4. Example of case study matrix for 1-story, 139 m² base-rectangular area, L-shape models

No.	Base-rectangular Area		Shape Ratio		Percent Cutoff		Percent Openings						Garage Door
	139 m ²	279 m ²	0.5	1.0	10	30	60/60	60/30	60/0	30/30	30/15	30/0	
L1	X		X		X			X					
L2	X		X		X			X					X
L3	X		X		X				X				
L4	X		X		X				X				X
L5	X		X		X						X		
L6	X		X		X						X		X
L7	X		X		X							X	
L8	X		X		X							X	X
L9	X		X			X		X					
L10	X		X			X		X					X
L11	X		X			X			X				
L12	X		X			X			X				X
L13	X		X			X					X		
L14	X		X			X					X		X
L15	X		X			X						X	
L16	X		X			X						X	X
L17	X			X	X		X						
L18	X			X	X		X						X
L19	X			X	X					X			
L20	X			X	X					X			X
L21	X			X		X	X						
L22	X			X		X	X						X
L23	X			X		X				X			
L24	X			X		X				X			X

Table 5. Summary of total number of representative models

Number of representative models			
Shape	1-story	2-story	Total
R	24	24	48
L	48	48	96
T	72	48	120
U	72	48	120
Z	48	48	96
			480

Table 6. CUREE parameters for 2.4 m (8 ft) by 2.4 m (8 ft) GWB wall model

Parameter	Value
K_0	2.60 kN/mm (14,846 lb/in)
F_0	3.56 kN (800 lb)
F_1	0.80 kN (179.8 lb)
r_1	0.029
r_2	-0.017
r_3	1
r_4	0.005
x_u	24.00 mm (0.9449 in)
α	0.8
β	1.1

Table 7. Seismic region definition

Region of Seismicity	Spectral Acceleration (short period or 0.2 sec)	
	FEMA 154	This project
Z1: Low	< 0.167g	< 0.167g
Z2: Moderate	$\geq 0.167g$	$\geq 0.167g$
	< 0.50g	< 0.50g
High	$\geq 0.50g$	-
Z3: High 1	-	$\geq 0.50g$ < 1.00g
Z4: High 2	-	$\geq 1.00g$ < 1.50g

Table 8. Performance grade conversion criteria

Grade	Conversion Criteria
4	Max. drift \leq 1% (IO)
3	1% < max. drift \leq 2% (LS)
2	2% < max. drift \leq 3% (CP)
1	3% < max. drift \leq 10%
0	Max. drift > 10%

Table 9. Minimum and maximum values of average performance grades (G_{avg}) classified by number of floors and base-rectangular area

No	Number of Floors	*Group Code	Base-rectangular Area, m ² (ft ²)	LOW		MODERATE		HIGH 1		HIGH 2	
				min	max	min	max	min	max	min	max
1	1	1-S	139 (1,500)	4.0	4.0	3.2	4.0	1.8	3.2	0.6	3.2
2	1	1-L	279 (3,000)	4.0	4.0	3.2	4.0	1.1	3.2	0.2	2.3
3	1	1-XL	418 (4,500)	4.0	4.0	2.9	3.9	0.9	3.1	0.2	1.4
4	2	2-S	2x166 (2x1,250)	3.7	4.0	2.6	3.8	0.8	2.6	0.2	1.1
5	2	2-L	2x232 (2x2,500)	3.4	4.0	1.8	3.4	0.4	1.6	0.1	0.7

*Group code is designated as: number of floors – relative size of base-rectangular area (S: small, L: large, XL: extra large)

Figure Captions

Figure 1 Composition of plan shapes in terms of base-rectangular area ($a \times b$) and cutoff areas (grey-shaded)

Figure 2. Average performance grades of all models for each seismic region

Figure 3. Effect of base-rectangular area (1-story, $R = 1.0$)

Figure 4. Effect of base-rectangular area (2-story, $R \neq 1.0$)

Figure 5. Effect of percent openings and garage door (1-story, L-shape, 139 m^2 ($1,500 \text{ ft}^2$) base-rectangular area, $R = 0.5$, $C_p = 10\%$)

Figure 6. Effect of percent openings and garage door (2-story, L-shape, $2 \times 232 \text{ m}^2$ ($2 \times 2,500 \text{ ft}^2$) base-rectangular area, $R = 0.5$, $C_p = 10\%$)

Figure 7. Histograms of maximum differences of G_{avg} between L, T, and Z shapes

Figure 8. Grading sheet for 1-story L, T, and Z shapes

Figure 9. Grading sheet for 2-story L, T, and Z shapes

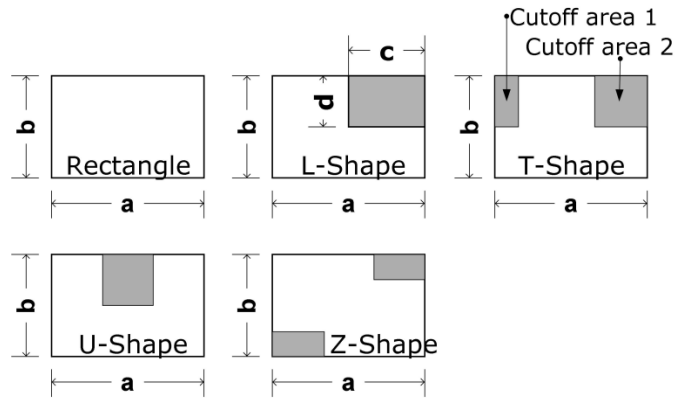


Figure 1 Composition of plan shapes in terms of base-rectangular area ($a \times b$) and cutoff areas (grey-shaded)

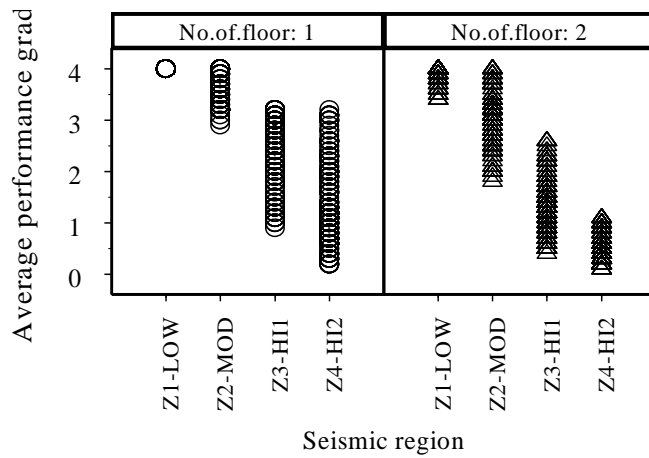


Figure 2. Average performance grades of all models for each seismic region

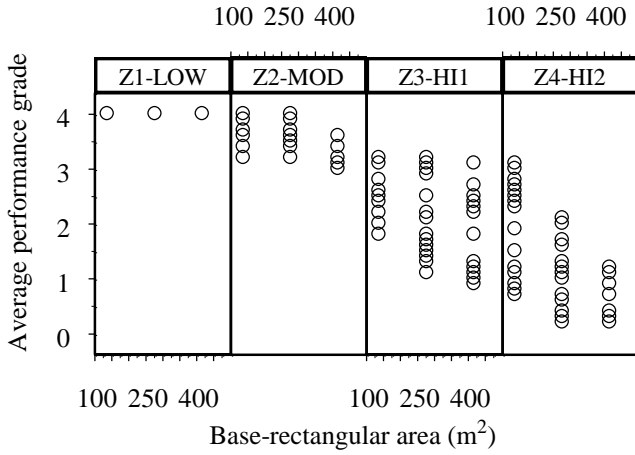


Figure 3. Effect of base-rectangular area (1-story, $R=1.0$)

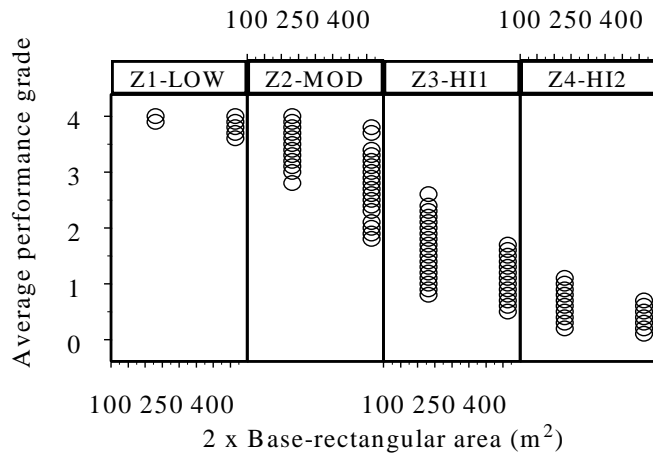


Figure 4. Effect of base-rectangular area (2-story, $R \neq 1.0$)

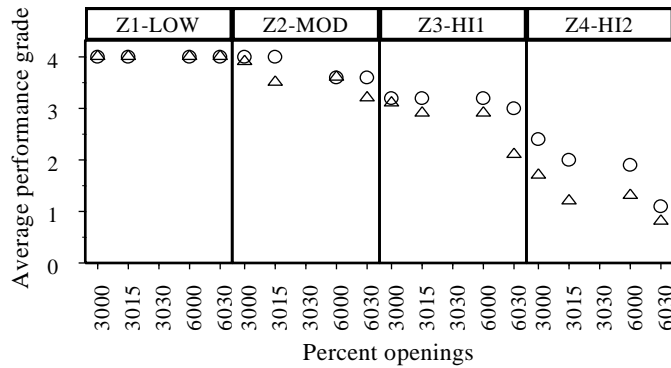


Figure 5. Effect of percent openings and garage door (1-story, L-shape, $139 m^2$ ($1,500 ft^2$) base-rectangular area, $R=0.5$, $C_p=10\%$)

Note: Triangular dots represent cases with garage door.
Circular dots represent cases with no garage door.

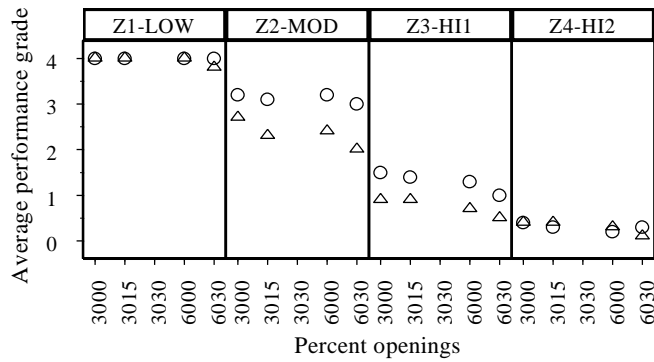


Figure 6. Effect of percent openings and garage door
(2-story, L-shape, 2x232 m² (2x2,500 ft²)
base-rectangular area, R= 0.5, Cp= 10%)
Note: Triangular dots represent cases with garage door.
Circular dots represent cases with no garage door.

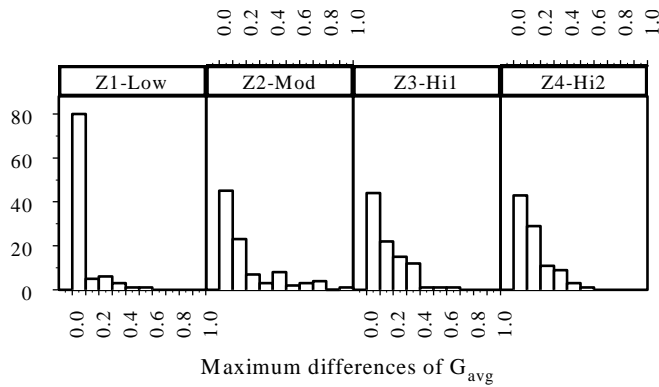
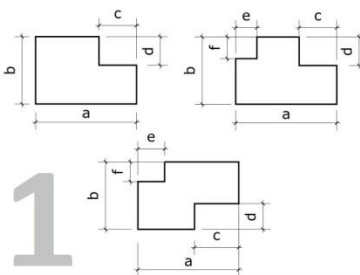


Figure 7. Histograms of maximum differences of G_{avg} among L, T, and Z shapes

1 Story L,T,Z - Shape



Performance Limit

- 4 Immediate Occupancy
- 3 Life Safety
- 2 Collapse Prevention
- 1 3% < max drift ≤ 10%
- 0 max drift > 10%

1

Address : _____

Lat. _____ Long. _____

Inspector _____ Date _____

Seismic Intensity

Hazard Map 2008 U.S. Geological Survey (USGS) National Seismic Hazard Maps

Hazardous Level	Sa (g)
10% of being exceeded in 50 yrs	1.0
2% of being exceeded in 50 yrs	

4

Shape Parameters

Overall Shape

Building Length, a	18.3 m. (60 ft)
Building Width, b	15.2 m. (50 ft)
Overall Shape Ratio, R= b/a	0.83
Based Rectangle Area, A= a X b	279 sq.m. (3,000 sq.ft.)

Cutoff Area 1

Cutoff Area 1 Length, c	5.2 m. (17 ft)
Cutoff Area 1 Width, d	5.2 m. (17 ft)
Cutoff Area 1, CA1= c X d	27 sq.m. (290 sq.ft.)

Cutoff Area 2

Cutoff Area 2 Length, e	N/A
Cutoff Area 2 Width, f	N/A
Cutoff Area 2, CA2= e X f	N/A
Total Cutoff Area, CA= CA1 + CA2	N/A

Percent Cutoff

Percent Cutoff, Cp= 100*(CA/A)	9.7	%
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Openings

Percent Openings on Long Side	60	%
Percent Openings on Short Side	30	%
Garage Door	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	

LOW (0.167g)

Based Area	139 sq.m. (1,500 sq.ft.)				279 sq.m. (3,000 sq.ft.)			
Overall Shape	Square		Rectangle		Square		Rectangle	
Cp (%)	10	30	10	30	10	30	10	30
Basic Score	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Percent Opening (Long Short)	60 60	0.0	0.0			0.0	0.0	
	60 30			0.0	0.0			0.0
	60 0			0.0	0.0			0.0
	30 30	0.0	0.0			0.0	0.0	
	30 15			0.0	0.0			0.0
	30 0			0.0	0.0			0.0
Garage Door	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Final Score								

MODERATE (0.5g)

Based Area	139 sq.m. (1,500 sq.ft.)				279 sq.m. (3,000 sq.ft.)			
Overall Shape	Square		Rectangle		Square		Rectangle	
Cp (%)	10	30	10	30	10	30	10	30
Basic Score	4.0	4.0	4.0	4.0	3.6	4.0	3.6	4.0
Percent Opening (Long Short)	60 60	-0.8	-0.4			-0.4	-0.8	
	60 30			-0.4	0.0			-0.4
	60 0			-0.4	0.0			-0.4
	30 30	0.0	0.0			0.0	0.0	
	30 15			0.0	0.0			-0.4
	30 0			0.0	0.0			0.0
Garage Door	0.0	-0.2	-0.5	-0.7	-0.1	-0.1	-0.4	
Final Score								

HIGH 1 (1.0g)

Based Area	139 sq.m. (1,500 sq.ft.)				279 sq.m. (3,000 sq.ft.)			
Overall Shape	Square		Rectangle		Square		Rectangle	
Cp (%)	10	30	10	30	10	30	10	30
Basic Score	3.2	3.2	3.2	3.2	3.0	3.2	3.0	3.2
Percent Opening (Long Short)	60 60	-0.7	-0.1			1.7	-1.1	
	60 30			-0.2	-0.1			-1.1
	60 0			0.0	0.0			-0.4
	30 30	0.0	0.0			0.0	0.0	
	30 15			0.0	0.0			-0.5
	30 0			0.0	0.0			0.0
Garage Door	-0.3	-0.3	-0.9	-0.7	-0.2	-0.6	-0.6	
Final Score							1.3	

HIGH2 (1.5g)

Based Area	139 sq.m. (1,500 sq.ft.)				279 sq.m. (3,000 sq.ft.)			
Overall Shape	Square		Rectangle		Square		Rectangle	
Cp (%)	10	30	10	30	10	30	10	30
Basic Score	2.6	3.1	2.4	3.1	1.2	2.0	1.2	1.9
Percent Opening (Long Short)	60 60	-1.5	-1.9			-0.6	-1.3	
	60 30			-1.3	-1.3			-0.6
	60 0			-0.5	-0.5			-0.2
	30 30	0.0	0.0			0.0	0.0	
	30 15			-0.4	-0.5			0.0
	30 0			0.0	0.0			0.0
Garage Door	-0.4	-0.3	-0.9	-1.2	-0.3	-0.4	-0.4	
Final Score								

Plan Sketch

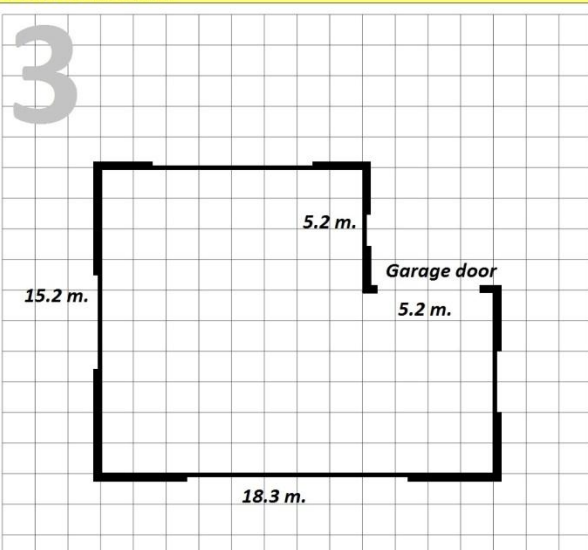


Figure 8. Grading sheet for 1-story L, T, and Z shapes

2 Story L,T,Z - Shape									
				Performance Limit <div><div></div>4 Immediate Occupancy <div></div>3 Life Safety <div></div>2 Collapse Prevention <div></div>1 3% < max drift ≤ 10% <div></div>0 max drift > 10%</div>					
LOW (0.167g)									
Base Area		2 x 1250 sq.ft.				2 x 2500 sq.ft.			
Overall Shape		Square		Rectangle		Square		Rectangle	
Cp (%)		10	30	10	30	10	30	10	30
Basic Score		4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Percent Opening (Long Short)	60 60	0.0	0.0			-0.6	0.2		
	60 30			0.0	0.0			-0.1	0.0
	60 0			0.0	0.0			0.0	0.0
	30 30	0.0	0.0			0.0	0.0		
	30 15			0.0	0.0			0.0	0.0
	30 0			0.0	0.0			0.0	0.0
Garage Door		-0.2	0.0	-0.1	-0.1	0.0	-0.2	-0.3	-0.4
Final Score									
MODERATE (0.5g)									
Base Area		2 x 1250 sq.ft.				2 x 2500 sq.ft.			
Overall Shape		Square		Rectangle		Square		Rectangle	
Cp (%)		10	30	10	30	10	30	10	30
Basic Score		3.2	3.2	3.2	3.5	3.2	3.3	3.2	3.2
Percent Opening (Long Short)	60 60	0.0	0.0			-0.5	-0.7		
	60 30			0.0	-0.3			-0.2	-0.1
	60 0			0.0	-0.3			0.0	0.0
	30 30	0.0	0.0			0.0	0.0		
	30 15			0.0	-0.1			-0.1	0.0
	30 0			0.0	0.0			0.0	0.0
Garage Door		-0.4	-0.1	-0.2	-0.2	-0.7	-0.2	-1.1	-1.3
Final Score									
HIGH 1 (1.0g)									
Base Area		2 x 1250 sq.ft.				2 x 2500 sq.ft.			
Overall Shape		Square		Rectangle		Square		Rectangle	
Cp (%)		10	30	10	30	10	30	10	30
Basic Score		1.9	2.5	2.2	2.4	1.4	1.5	1.4	1.4
Percent Opening (Long Short)	60 60	-0.8	-1.1			-0.6	-0.6		
	60 30			-0.8	-1.0			-0.5	-0.4
	60 0			-0.7	-0.5			-0.4	-0.2
	30 30	0.0	0.0			0.0	0.0		
	30 15			-0.5	-0.3			-0.1	-0.1
	30 0			0.0	0.0			0.0	0.0
Garage Door		-0.3	-0.3	-0.9	-0.9	-0.3	-0.3	-0.6	-0.6
Final Score									
HIGH2 (1.5g)									
Base Area		2 x 1250 sq.ft.				2 x 2500 sq.ft.			
Overall Shape		Square		Rectangle		Square		Rectangle	
Cp (%)		10	30	10	30	10	30	10	30
Basic Score		0.8	1.0	1.0	1.0	0.4	0.6	0.3	0.6
Percent Opening (Long Short)	60 60	-0.6	-0.8			-0.1	-0.4		
	60 30			-0.5	-0.6			-0.1	-0.4
	60 0			-0.4	-0.3			-0.1	-0.3
	30 30	0.0	0.0			0.0	0.0		
	30 15			-0.3	-0.1			-0.1	-0.3
	30 0			0.0	0.0			0.0	0.0
Garage Door		-0.1	-0.1	-0.7	-0.5	-0.2	-0.3	-0.1	-0.2
Final Score									

Figure 9. Grading sheet for 2-story L, T, and Z shapes